
CHAPTER 6

THE ELECTROMAGNETIC FIELD AS A BIOLOGICAL VARIABLE

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INTRODUCTION

There are epidemiological studies that have related 50/60-Hz power frequency fields to childhood leukemia.¹⁻⁴ The remarkable thing about these reports is that the magnetic field intensities that are implicated are so small that no reasonable explanation yet proposed has successfully characterized the underlying interaction in purely physical terms. Physics uses a special word, *weak*, to describe effects which appear to occur at energies too low to be reconciled with existing theory. Electromagnetic signals at 50 and 60 Hz fall within a band of frequencies that is referred to as extremely low frequencies, or ELF. Thus the description, *weak ELF* magnetic fields.

Very fundamental biological questions are involved. The question of magnetic fields and cancer is merely the tip of the proverbial iceberg, with more implications below the surface than observations above. There are a number of reasons for the heightened scientific excitement concerning ELF magnetic field interactions. Whenever there is a theoretical impasse in science, such that observations outstrip explanation, there is always the possibility for paradigmatic change, with the concomitant discovery of fundamentals that have heretofore been missed. Adair⁵ has facetiously suggested that the laws of physics have to be rewritten to accommodate the ELF observations. However, this misses the mark, even in jest. It is obvious that Maxwell's equations and quantum mechanics are not going to be changed one whit as a result of observations on ELF biointeractions. It is reasonable, however, to expect that if the ELF observations hold up, a restructuring of some basic concepts in biology will be necessary. These may very well

include fundamental questions in biological development, circadian rhythms, the immune response, neurobiology, etc. However, in the following, I wish to explore another question, inquiring whether the ELF interactions imply a deeper relation between electromagnetic fields and living systems. Stated directly, I ask: does the ability of weak ELF signals to perturb living systems indicate that these signals are interacting with an intrinsic electromagnetic characteristic of these systems? This does not mean that the experimental analysis of these perturbations necessarily rules out finding specific interactions with various molecular or biochemical entities, but it does mean that these entities are perhaps only vehicles through which the electromagnetic flavor of living systems is expressed. The role of enzymes, reaction kinetics, molecular biology and the like are unchanged, but there is an underlying electromagnetic framework that transcends these entities. In other words, do living systems contain a hidden electromagnetic variable?

THE PHYSICAL INTERACTION

Although there is still considerable discussion about the nature of the physical interaction between weak magnetic fields and biological systems, increasing evidence appears to point to the idea that some sort of resonance mechanism underlies the ELF reports. The ion cyclotron resonance (ICR) hypothesis was introduced by the author in 1984.⁶ A long list of experiments based on this idea have been attempted, with mixed results. There have also been attempts to put the original hypothesis on a sounder theoretical basis^{7,8} and to develop similar concepts.⁹ Additional, nonresonance models to explain the ELF interaction have also been advanced^{10,11} but to date these have not led to supportive experiments, with one notable exception, namely the possibility that Faraday induction may underlie some or all of the experimental reports. Michael Faraday first observed, about 150 years ago, that conducting materials in the vicinity of changing magnetic fields develop internal electric currents. The magnetic fields associated with electric power lines in North America are

changing at the rate of 60 times per second (60 Hz), and it is reasonable to think that humans, as electrical conductors, will consequently experience induced currents in the vicinity of power line fields. However, the intensity of such currents, readily calculable, is found to be vanishingly small, and it is unlikely that Faraday induction is the underlying reason for most of the weak ELF magnetic field reports. This is not meant to totally rule out the possibility of Faraday interactions. If we are observing a general perturbation of an electromagnetic framework, as stated above, it is reasonable to expect that more than one interaction mechanism is possible.

Nevertheless, a resonance mechanism would have distinct advantages. In many other areas, resonance mechanisms often are capable of providing coherent outcomes at energy levels that might otherwise be lost in the noise. To a great extent, when resonance is involved, frequency becomes a variable that is as important as energy. It doesn't take much energy for a parent to keep elevating a child on a swing providing the pushes occur at the resonance frequency, that is, again and again at the precise moment when the swing is at the top of its path.

Consider the natural way the magnetic field of the earth, i.e. the geomagnetic field, is involved in an ICR effect. Cyclotron resonance requires the simultaneous application of a static (dc) magnetic field and a periodic field (magnetic *or* electric). It happens that the level of dc magnetic field required for ionic resonances at ELF frequencies is in the range of the earth's magnetic field (approximately 250 to 600 milligauss). This suggests that the reported ELF responses may result from an intrinsic biomagnetic property that has evolved in living systems since life began on earth some 3.5 billion years ago. Considering that the geomagnetic field was probably formed about 4.5 billion years ago, it is likely that the evolutionary process would have incorporated the geomagnetic field into the way living things presently function. In the words of Skiles,¹²

"...the existence of the geomagnetic field preceded the origin of life on earth, so that

evolution has occurred in the presence of the geomagnetic field....hence it would indeed be surprising if the world were devoid of species capable of detecting, and deriving selective advantage from, the geomagnetic field."

The most attractive features of the cyclotron resonance hypothesis are first, the straightforward way certain frequencies fall out of the underlying relationship, and second, the specific involvement of biologically important ions such as Ca^{2+} , Mg^{2+} , and K^{+} . The relationship between frequency and field is given by:

$$2\pi f = (q/m)B.$$

This equation, commonly used in physics to describe the properties of charged particles in a magnetic field in vacuum, relates the resonance frequency f of such particles to the product of the charge-to-mass ratio of the particle and the dc magnetic field B in which the particle moves. In physics the frequency is usually associated with particle motion in a circle or a helix. Not only f , but multiples of f also provide resonant conditions. The charge-to-mass ratios of biological ions are known to great precision, and so one can readily calculate what the resonant frequencies of a given ionic species should be for any value of the dc field. The expression for the cyclotron resonance frequency, as given above, is totally independent of kinetic parameters such as velocity, orbital radius and energy. Given one particular combination of charge-to-mass ratio (q/m) and magnetic field B , the frequency f is precisely the same, whether the particle circulates in a radius of 5 Å or 5 m.

Despite its intellectual appeal, there are critically difficult problems attached to this idea. For one thing, the interior of cells can hardly be characterized as vacuum-like. Also, it is difficult to imagine the necessarily small energies involved in this process not being swamped out by the ubiquitous, orders-of-magnitude larger, mean thermal energy that dominates the kinetics of the cell. Even sharply defined resonances can be defeated with sufficient damping. (Try pushing a swing under water). The author initially

suggested that ion channels might be affected by ELF magnetic fields. They exhibit unusually low damping, mainly because the interior of channels, even if not vacuum-like, certainly does not lead to the sort of scattering that one normally finds elsewhere in biological materials. In addition, from a biological standpoint the ion channel represents a prime suspect in searching for a possible interaction site. Membrane channel proteins exhibit helical internal symmetries and convey large amounts of electric charge in coherent, directed ways, properties that might indicate a potential for magnetic interactions. In addition, channel transport is a key factor in cell metabolism. Any effect on transport processes results in possible physiological leverage. The smallest of changes in channel activity that might result from magnetic fields would alter biological response.

As an alternative to the ion channel interaction, Lednev⁹ has hypothesized that calcium-binding proteins, notably calmodulin, exhibit resonance properties in magnetic fields. Again, as in the channel concept, the signature of the Lednev interaction carries the charge-to-mass ratio specific to ion cyclotron resonance, with, however, additional information concerning the intensity of the magnetic signal. Because of their involvement in cell signalling, these proteins also carry great physiological leverage: subtle changes in activation can lead to cascades downstream.

CALCIUM OSCILLATIONS

The author¹³ has suggested a new approach to the question of the ELF interaction, pointing out that ELF fields may indirectly affect the cell signalling apparatus by either reinforcing or altering the frequency of the intrinsic Ca^{2+} oscillations in the cytosol. It has become evident that the low-frequency oscillatory behavior referred to as Ca^{2+} oscillations is not limited to excitable cells, but is actually a somewhat common property of most, if not all, living cells.¹⁴ Ca^{2+} oscillations are characterized by a variety of waveforms, spike-like as well as sinusoidal, with frequencies extending down from just a few Hz to well below .05 Hz. These oscillations occur as a result of complex interactions

among calcium channels, enzymatically driven calcium pumps, and calcium pools. Intrinsic to the oscillatory process is the release of calcium from intracellular stores such as those within the endoplasmic reticulum when inositol (1,4,5)-trisphosphate (InsP₃) binds to its receptor.

The most surprising thing about these oscillations is that they are not haphazard and nonfunctional, but apparently represent an intrinsic feature of the signalling apparatus of the cell. Some observers¹⁵ have concluded the Ca²⁺ oscillator in cells is an integral component of a sophisticated signalling system that is frequency encoded, i.e., is capable of conveying information to the cell using a code based upon frequency. This follows the observation that the measured oscillation frequency in a variety of cell types is directly proportional to agonist dose. Frequency encoding in the calcium signalling apparatus may imply that specific frequencies externally applied to the cell can deliver "false" messages, i.e. messages derived from frequencies other than the one encoded by the local agonist. Alternatively, one can also conceive of situations where an external signal might reinforce a specific message because the external signal is at the "correct" frequency. I have suggested¹³ that if ELF magnetic (and electric) signals are capable of perturbing the oscillator, then one should expect that they should both enhance and hinder biological function, depending upon the frequency.

Interactions of this sort would be far more direct than previous ELF model mechanisms involving specific sites such as receptors, ion channels, and calcium-binding proteins. Any possible direct interaction of ELF fields with messenger frequency, even at subtle energies, carries an enormous potential for altering biological information transfer, if indeed frequency encoding is intrinsic to the calcium signalling apparatus. Above all, this concept avoids the ticklish question of how the ultra-low energies associated with weak electromagnetic fields can physically be detected by cells, placing the focus more squarely on frequency instead of energy.

Even if the question of physical mechanism were laid to rest, the other question

would still remain: Are these ELF interactions revealing something basic about living systems? This is clearly a speculative question which is best approached in the most general terms.

IS THERE AN ELECTROMAGNETIC BASIS FOR LIFE?

It is agreed that there are *presently* four types of force fields present in nature (*presently*, because in the remote past, two or more of these four fields might have been indistinguishable). These are categorized as *gravitational, strong, weak, and electromagnetic*. It is important to realize that every species of matter is contained within one or more of these four categories. The world we see around us exhibits unique features that reflect these forces. Stated in another way, these features can also be regarded as inevitable consequences of these forces. For example, we do not think it unusual that the planets move in elliptical orbits around the sun, since this type of motion is predicted by the laws of gravitation. If we ask what manifestations appear in nature because of the electromagnetic field of force, we find that its mere existence makes the formation of atoms and molecules, and even organic polymers inevitable. It may not be too great a jump to extend this argument to life itself, maintaining that living systems are also an inevitable consequence of the electromagnetic field. At the very least, as far as living things are concerned, the electromagnetic category is the most obvious of the four. I argue that if the very origin of life is necessarily rooted in electricity and magnetism, one might expect to find that electromagnetic effects are interwoven into the way all living things function.

BIOLOGICAL DEVELOPMENT

The underlying role that electromagnetism plays in biological development is hinted at in many experiments yet remains one of the most elusive problems. Much more has been done in examining the potential *electric* connections to embryology as compared to *magnetic* interactions. It is interesting to consider possible explanations for development based upon the electromagnetic

field per se. Indeed, the word "field" is already used by embryologists as a term to describe the net three-dimensional force equivalent that drives the morphological outcome, albeit with a physical meaning that is totally distinct from electromagnetism. Indeed, electric and magnetic aspects are included by theoretical biologists merely as additional tissue properties akin to all the other characteristics derived from such nonelectromagnetic "fields". These have been based on widely different ideas: to name only a few, the self-organizing Turing field,¹⁶ the phase-shift model,¹⁷ the phosphorylation field,¹⁸ models based on mechanical forces,¹⁹ and Sheldrake's morphic field.²⁰ Nuccitelli²¹ has suggested a role for transcellular ion currents in morphogenesis, but discounts the possibility that electrical potentials play a primary role in development as "unrealistic". Intrinsic to all but Sheldrake's distinctly aphysical approach is the notion that such "fields" have to be consistent with evolution, i.e. would have been arrived at through natural selection, as a consequence of the immense number of trials and rejections that are at the heart of the evolutionary process.

It is surprising that so little attention has been paid to possible explanations based on the electromagnetic field itself. Each of the "field" concepts listed above can be regarded as based on a set of observable characteristics, secondary to a defining, all-inclusive electromagnetic field. In essence, any electromagnetic field is produced merely by the presence of source charge distributions at rest and in motion, conditions obviously satisfied by everything alive. Further, fields arising from such sources may in turn interact with the sources, in time leading to redistributions of charge and thus to new field values. It is conceivable that such a process, as it unfolds in time, may be intrinsic to the sequence of events we call biological development. Conceptually, this picture inverts the approach described by the examples given above. That is to say, the structures that are nominally used to describe morphogenetic events would be, in effect, instruments of the defining field. The electromagnetic field specific to an organism would provide a map

or template for tissues to grow into. Not unlike other "field" concepts, the template and its organizational development would be for the most part evolutionarily conserved, with changes in speciation occurring because of perturbations in the source charge distribution.

This idea is not entirely new. For many years, chiefly in the thirties at Yale, Sterling Professor Harold Saxton Burr²² propounded the concept that there is an "electrodynamical" complex in all living systems that he called the "L-field" (life field). The L-field was contrived to deal with the difficult question of the control mechanism in homeostasis. Although he recognized the intrinsic value of the field concept in pursuing the problem of embryological alignments, Burr conceived of this field as somehow connected to surface currents and not derived from structural properties intrinsic to the system.

It has also been known for many years that simple, reproducible patterns of electric potential can be found on the surfaces of many cells. Pohl²³ displayed the electric potentials external to one-celled organisms using ferroelectric particles mixed directly within the *in vitro* medium. Even earlier, similar observations were related to the possibility of an intrinsic electric field by Lund.²⁴ He wrote, commenting on his work on algal cells,

"...since the electrically conducting medium provides a return circuit, it is evident that...there exists a system of electric currents in the medium which constitutes the external electric field of the polar cell."

Although Lund's student, Jaffe, and Jaffe's students, in turn,²⁵ considerably advanced the experimental approach for such measurements with the use of a vibrating probe electrometer to measure current densities in the pericellular medium, they shifted attention away from Lund's original emphasis on the field. Emphasis was instead placed on the well-ordered ionic currents observed external to a number of embryological systems; in some cases these currents, measured in terms of calcium ion flow, were shown to be directly linked to the process of embryological development. This line of investigation has focused in on the role of such calcium currents, but at the same time has generally

steered clear of any discussion regarding underlying physical mechanisms based on fields. Nevertheless, one can argue that the observed patterns of transmembrane current can be ultimately explained in terms of an intrinsic electric field within the developing organism.

Following the discovery by Fukada²⁶ that collagenous tissues such as tendon and bone exhibit stress-dependent potential differences over distances greatly in excess of single-cell dimensions, various observers have attempted to formulate some sort of global process that might explain large-scale differentiation and control in terms of field gradients. As a result of dc surface potential measurements in different animals, Becker²⁷ concluded that living systems possess a primitive adjunct to the central nervous system that manifests itself as a specific pattern or field of dc potentials. This field, a "*representation of the entire organism as a functional unit*", was hypothesized both to sense trauma as well as to initiate repair processes. A later version of this concept²⁸ suggested that Wolff's Law, the adaptability of living bone to remodel under impressed mechanical forces, can be explained in terms of the relative response of bone cells to the distribution of piezoelectric and/or streaming potentials within the affected limb.

The most specific of all such attempts to reconcile electricity and development was that made by Athenstaedt,²⁹ perhaps the first to measure regular, consistent changes in electric polarization in different tissues as a function of development time. He also suggested, in no uncertain terms, that there was a close connection between electric polarization and embryological growth:

"It is assumed that a definite alignment of permanent electric moments of polar molecules occurs during the first few weeks of embryonic development outside the perichordal tube and the sclerotome and scleromite boundaries. The alignment... which occurs at this early stage is probably identical to [those] which are demonstrable through life in the ligamenta longitudinalia and the disci intervertebrales."

This remarkable statement is quite different from previous concepts which merely

suggested that the maintenance of potential differences within an organism provides the system with the possibility of an on-board mechanism for monitoring and controlling homeostatic and repair functions. Not only did Athenstaedt focus in on the electric field but he related these embryonic fields to later development.

THE π -VECTOR FIELD

How can one go about describing an intrinsic electromagnetic field? If one imagines only the electrostatic E-field arising from an array of many charge sources that are fixed in place, the topological complexity of electric fields is potentially enormous. Consider Figure 6.1, which maps out the electric field lines for five relatively simple cases, from that of a single positive charge to pairs of unequal, opposite charges. The field plots are merely represented in two dimensions, because all the cases shown enjoy a high degree of symmetry. It would be difficult (although not impossible) to construct similar plots of the electric field map resulting from millions of such charges laid out in three dimensions. In living systems there is the added complexity that the charge distribution arising from polar molecules, ions in solution, and distributed van der Waal's potentials changes in time, as these and other sources physically move from point to point, recombine and reappear. The net electric field for any organism is therefore tremendously complex, both spatially and temporally. Further, any change in motion will result in the creation of local magnetic fields, which in some cases could be significant if the charge motion is correlated, i.e., acts in concert in a manner that results in a magnetic field that adds instead of cancelling.

However, the great complexity of the electric and/or magnetic field distributions that is associated with living organisms has an important corollary. One can look at the other side of this picture, and state that the complexity of such electromagnetic fields necessarily implies that they must also carry enormous amounts of information.

Although the field vectors E and B can in this way be directly utilized, E to describe the

electric component and B the magnetic component, there is an alternative description. It is not necessary to separate out the electric and magnetic aspects of the field. There is a unique field vector, introduced by Hertz over a hundred years ago, that can be regarded as a single expression covering the joint distributions of magnetic and electric fields. The Hertz vector Π can be used to describe the electromagnetic field over all space that results from the static and moving charge distributions within a living organism. The Π -field provides a unique characterization for any living thing: at any instant, $\Pi = \Pi(r)$, such that it varies from point to point within the organism. It is even more meaningful to realize that this field also varies with time, such that $\Pi = \Pi(r,t)$. Thus, the biological template can be described by a single observable, and, the question of development can be reduced to determining the factors that govern the time variation of $\Pi(r,t)$. This abstract device is obviously difficult to deal with on a molecular level. The interior of living things is far too complex to permit a straightforward detailed representation of Π . Even if we were able, somehow, to come up with such a detailed description, this would still not solve the central problem of development, namely what causes the Π -field not only to developmentally change in the way it does, but to also change in the species-consistent way it does.

Nevertheless, framing the problem in electromagnetic terms does have certain advantages. For one thing, the properties of electromagnetic fields are as well understood as anything under the sun. We have already seen that there is limited experimental evidence for this electromagnetic field concept, and, unlike many other ideas there is no limit to the variety of experiments that can be used to test this hypothesis. Above all, this description also carries the seed of a larger idea connected to evolutionary processes. If organisms carry

an electromagnetic template that can be described in terms of a vector field, then it is reasonable to suggest that changes in speciation can also be associated with changes in the Π -vector. Carrying this idea to its logical extreme, I can suggest that the entire process of evolution is equivalent to the slow changes in this electromagnetic field complex.

Biologists, even before Darwin's time, have used words such as "characteristic" or "visible character" to describe the aspects of living things that we see directly: the color of the eyes, the shape of a bird's beak, the

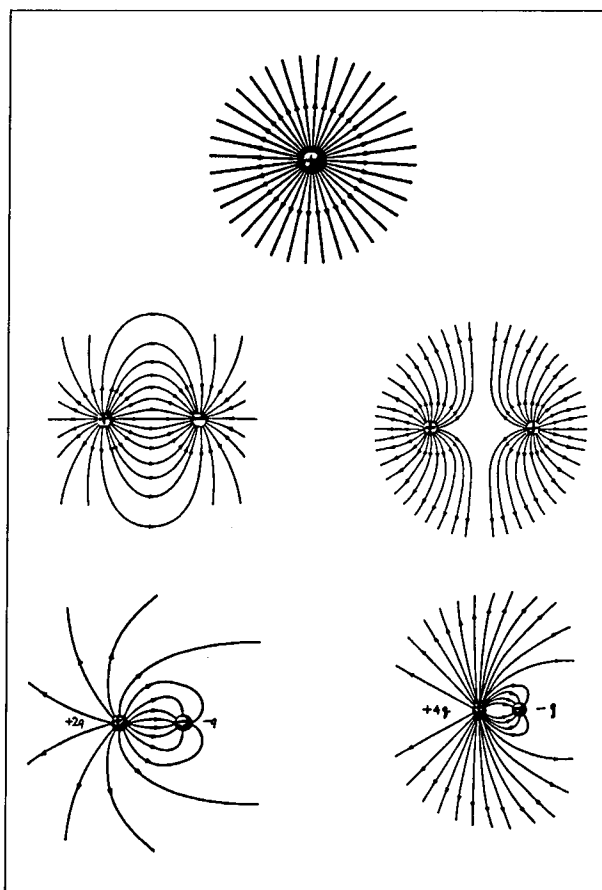


Fig. 6.1 The electric fields arising from five simple charge arrays. For the single positive charge at the top, a radial field results. The middle set shows the fields corresponding to two equal and unlike charges, on the left, and two equal, like charges on the right. The bottom set shows the field distribution from a pair of unlike charges where one is twice the magnitude of the other, on the left, and where one charge is four times the other, on the right.

height of an individual, the length of a giraffe's neck, etc. Any such characteristic is the result of a specific gene-complex with a given set of environmental conditions. When we say that the outward characteristics are determined by genes, we also maintain that there is a transformation of information between gene and characteristic. If one were to examine a set of genes in an imaginary high-power microscope that had sufficient resolution to allow great detail, it would still be extremely difficult to predict, by visible examination alone, the characteristics to which these genes were connected.

Consider the likelihood that still another transformation may exist, one that relates the electromagnetic field to genes, such that the gene "field" is itself determined by the electromagnetic field. In this view the information content of a living system is given by specifying the field $\Pi(r,t)$. We all agree that genes express this information in a molecular format using the convenient properties of nucleic acids. Although the outward visible characteristics of an individual are the result of such gene expression, in principle they also can be represented in terms of a specific electromagnetic field. Genes then would merely act to store the details of this governing field, carrying this information from one generation to the next.

Evolution can therefore be regarded as equivalent to changes in this Π -field, changes that reflect both phylogenetic as well as ontologic outcomes. Note that all of the Darwinian processes, such as natural selection, would be unchanged by this field. Characteristics, however, are ultimately described, not in the usual anthropomorphic way, but in purely mathematical terms. Over the eons that life has evolved, a single descriptor emerges, namely the vector field $\Pi(r,t)$. This field description would fully define the individual, the species and all things that have lived. In this respect it would hardly be different from the relatively simple molecular genetic model we currently subscribe to. The critical difference would be in the relationship of electromagnetic fields to biological development.

ELECTROMAGNETIC RECAPITULATION

The concept of recapitulation introduced in the last century by Ernst Haeckel implies a pathway for development in which organisms pass through a sequence of embryonic stages that reflect the adult stages of the organism's more primitive ancestors. Despite its simplistic appeal, this concept is no longer in vogue. Instead, it is now generally agreed that the process of development merely requires that earlier stages be less complex than later stages, both ontogenically as well as phylogenetically.

This principle is in agreement with our hypothetical explanation of biological development as a spatiotemporal manifestation of an electromagnetic field complex that is genetically conserved over evolutionary times. Not only are these two views in agreement, but there is a remarkable parallel between what the biologist observes in development and what the physicist studies in electromagnetic theory. When comparing one to the other, one can point to the development of the science of electromagnetics, which builds in the most natural manner from simplicity to complexity. For example most textbooks in electricity and magnetism begin with a discussion of electrostatics, the fields resulting from one, two, or more charges that are strictly at rest. Subsequent development of this material leads to studies of the energies involved in displacing one charge in the field of another, a process that is generalized into the concept of potential difference. Later, depending on the amount of free charge, its mobility, and the molecular nature of a given material, potential differences applied to different types of substances can lead to polarization effects, on the one hand, or to conduction, on the other. Building further on this edifice, charge conduction is equivalent to current, which in turn is the source of magnetic fields.

One can speculate that the parallel between electromagnetic "development" and biological development may be more than merely philosophical. In other words, does biological development reflect an *electromagnetic recapitulation*, in which the unfertilized egg carries no free electric charge, but perhaps is electrically polarized, waiting for the pulse of free calcium that accompanies

fertilization? It has certainly often been speculated that the familiar ooplasmic animal/vegetal polarity is a consequence of an intracellular gradient in electrical potential. Following fertilization, does the increasing complexity of the organism reflect the involvement of more and more sophisticated levels of electromagnetics? It is conceivable that this concept may be testable, especially in terms of the potential gradients arising in the relatively simple course of events stretching from before fertilization to the gastrulation stage.

It is particularly interesting to dwell on the possible role that may be played by magnetic fields in the development process. The long series of experiments carried out by Leal's group³⁰ indicated that weak magnetic fields applied to chick eggs results in abnormal development. Although no abnormalities were observed by Cameron et al³¹ in exposing fertilized Medaka fish eggs to weak ELF magnetic fields, they did observe significant delays in embryonic development. It is typical of the bioelectromagnetics research area of the past few years that most of the interest in these reports has focused on the potential for hazard, instead of asking in the first place why embryological development should be sensitive to weak magnetic fields. Following the idea of *electromagnetic recapitulation*, one might argue that there are times during embryogenesis when intrinsic magnetic fields will be formed, and one might consequently expect that the organism would be most sensitive to external magnetic fields during this period. In this regard, it is worth noting that briefly occurring dipole magnetic fields in developing chick eggs have been detected using a SQUID magnetometer.³² However, subsequent comments surrounding these measurements have downplayed any functional role for the observed field. Consider the statement by O'Shea:³³ "These magnetic fields are too small to elicit any biologically useful action."

SUMMARY

One example of the weak fields that are sensed by living systems are extremely low frequency magnetic signals, which seem particularly effective in eliciting a wide range of

biological effects. The underlying mechanism in this case is very likely some sort of resonance phenomenon, perhaps one that shifts or reinforces the intrinsic dominant frequencies in the intracellular Ca^{2+} oscillator.

The fact that weak electromagnetic fields are capable of affecting biological response leads to a fascinating question. Are such observations merely one more physiological response to the environment, or do they reveal a hidden variable in biology?

One possible explanation for the variety of weak bioelectromagnetic responses is that living systems include an electromagnetic variable that has heretofore not been recognized. Even if this is true, does such a field play a central role in development? I hypothesize the existence of a primary electromagnetic template in living things that both plays a guiding role in development and is genetically conserved over evolutionary times. It is possible to formulate a single abstract representation of the electric and magnetic components of this spatiotemporal field by means of the Hertz vector, which in turn can be mathematically used to describe the course of evolution. Finally, one can replace the anthropomorphic description of the characteristics of living things with an equivalent field description, and, in principle, follow the developmental expression of these characteristics by means of the sequential development of the field from simple to complex, a process I term *electromagnetic recapitulation*.

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